

DIFFERENCES IN POSTURAL CONTROL RESPONSES TO LEVELS OF VISUAL OCCLUSION IN INDIVIDUALS WITH CHRONIC ANKLE INSTABILITY

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ABSTRACT

Lillian H. VanDeMark: Differences in Postural Control Responses to Levels of Visual Occlusion in Individuals with Chronic Ankle Instability
(Under the direction of Erik Wikstrom)

Chronic ankle instability (CAI) is a condition characterized by recurrent ankle sprains. Those with CAI are described as visually reliant due to postural control deficits observed under fully occluded visual conditions. Little is known about the influence of partially occluded vision on postural control in those with CAI. The purpose of this study was to examine the effect of CAI on postural control under progressive levels of visual occlusion and relate postural control under these conditions to visual function and sensory integration in those with CAI.

Thirty-five participants with CAI and sixteen controls completed postural control assessments under four visual conditions: 1) eyes-open, 2) low-occlusion, 3) high-occlusion, and 4) eyes-closed. Participants also completed visual performance (Senaptec Sensory Station) and sensory integration (Sensory Organization Test) assessments.

Both groups demonstrated worse postural control under limited-vision conditions compared to eyes-open. Some measures of visual performance predicted postural control under both eyes-open and limited-vision conditions.

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LIST OF ABBREVIATIONS

CAI	Chronic Ankle Instability
DLS	Double-Limb Support
COP	Center of Pressure
SOT	Sensory Organization Test
SLS	Single-Limb Support

CHAPTER I: INTRODUCTION

Chronic ankle instability (CAI) is a costly and disabling condition characterized by recurrent sprains, episodes of giving way, pain, and/or weakness that linger after an injury to the ankle, typically a lateral ankle sprain.^{1,2} Ankle sprains are one of the most common injuries treated by health care professionals, with an estimated 23,000 ankle sprains occurring per day in the United States.³ Approximately 40% of these individuals develop CAI as a result⁴ which may lead to further disability including post-traumatic osteoarthritis in the ankle joint^{5,6} and decreases in physical activity^{7,8}.

Individuals with CAI have sensorimotor adaptations that are a result of the initial ligamentous injury⁹ and lead to deficits in postural control. These adaptations include altered somatosensory input and neuromuscular response. A cascade of events is thought to follow damaged mechanoreceptors upon initial injury leading to long lasting altered cortical level somatosensory integration.⁹⁻¹¹ First, the initial ligamentous injury interrupts continuous somatosensory input from the joint regarding joint position sense, joint stress, and joint velocity.^{9,11} Without this information, the motor component of the sensorimotor system must adopt a new strategy of obtaining sufficient information to maintain postural control via dynamic joint stability.^{9,11} It appears that in the absence of sufficient somatosensory input, the motor control system reweights the level of visual feedback used to maintain postural control.⁹ Over time, the motor control system begins to rely on visual feedback to produce appropriate motor

responses. A recent meta-analysis found that individuals with CAI have significantly greater postural control declines during single-limb balance tasks under eyes-closed conditions compared to eyes-open.¹² This indicates that the sensorimotor system cannot compensate for the removal of vision and therefore suggests a reliance on visual information to maintain postural control.¹² It is unclear whether long-term visual reliance in CAI patients is a positive or negative adaptation. Reliance on information from the visual system to maintain postural control—due to dysfunctional somatosensory system integration—could leave the individual vulnerable to reinjury when the visual system is overloaded with tasks, such as in sport, when one has to identify and respond to multiple stationary and dynamic objects.¹¹ However, incorporating faulty somatosensory information to determine correct motor response may result in an incorrect response and, predispose an individual to injury.¹¹

Whether or not the adaptation of visual reliance is necessary or detrimental, the topic is worth exploring in future research. Current balance training methods often involve exercises in static posture with eyes-closed,^{13,14} but these do not alter visual reliance in CAI¹⁵. Incorporating dynamic postural exercises with limited visual information should be explored as a method of altering visual reliance. A study by Kim et al.¹⁶ found interrupting visual information with stroboscopic goggles caused significant postural instability during single-leg stance compared to eyes open conditions in healthy subjects. However, the current literature surrounding the postural response of the CAI population to interrupted visual information is limited. Therefore, the overall purpose of this study is to examine the difference in postural control response during varying levels of visual occlusion between those with CAI and healthy

controls. We will also relate postural control response under these conditions to visual and somatosensory function, and the sensory integration strategies in those with CAI.

Specific Aims

We will approach this topic with the following aims:

Aim 1: To specify changes in postural control during balance conditions with varying levels of visual occlusion in those with CAI and healthy controls.

Hypothesis 1: Both groups will demonstrate worse spatiotemporal postural control outcomes (shorter time to boundary) during balance conditions with any limitation in visual information (low occlusion, high occlusion, and eyes closed) compared to eyes open with no occlusion. Furthermore, those with CAI will have significantly worse postural control outcomes compared to healthy controls during all limited vision conditions.

Aim 2: To test the influence of visual function and performance measures on changes in postural control under varying levels of visual occlusion in those with CAI.

Hypothesis 2: Worse spatiotemporal postural control outcomes (shorter TTB) will be associated with poor visual performance scores on the Senaptec Sensory Station battery of vision and sensory performance tests, specifically the Perception Span, Eye-Hand Coordination, Go/No-Go, .

Aim 3: To test the influence of sensory integration measures on changes in postural control under varying levels of visual occlusion in those with CAI.

Hypothesis 3: Worse spatiotemporal postural control outcomes (shorter TTB) will be associated with decreased ability to utilize somatosensory input (lower SOM ratio

score) and decreased ability to utilize visual input (higher VIS ratio score) on the Sensory Organization Test under limited vision conditions.

CHAPTER II: REVIEW OF LITERATURE

Chronic Ankle Instability

Epidemiology

Chronic ankle instability (CAI) is a debilitating condition of the ankle joint characterized by recurrent sprains, episodes of “giving way”, pain, or weakness in the ankle.^{1,2,4} CAI arises from an acute sprain of the ankle. Acute ankle sprains are one of the most commonly occurring injuries seen in active populations^{17,18} regardless of competition level.¹ It has been estimated that over 11, 000 ankle sprains occur in collegiate athletics per year, accounting for 15% of all injuries.¹ Out of all ankle sprains, the most common type is the lateral ankle sprain, occurring due to overstretching of the lateral ligaments during extreme inversion.^{1,18} The majority of individuals who experience an acute ankle sprain go on to sustain one or more recurrent sprains.^{1,13} Yeung et. al. showed that the rate of re-injury across multiple competition levels was as high as 74%.¹ It has been estimated that 40% of individuals who sustain an ankle sprain develop CAI.⁴

Substantial costs are associated with ankle sprains including initial medical expenses, lost earnings, and reduced quality of life costs.⁵ In 2010, United States emergency departments saw over 1 million ankle sprains, charging an average of \$1,211.15 for initial treatment.¹⁸ These costs do not consider long-term effects of ankle sprains/CAI such as decreased physical activity and post-traumatic osteoarthritis in the

ankle.^{6,7} An arthroscopic study done on individuals with CAI prior to surgical reconstruction of the ankle ligaments showed that 55% of participants had either lateral or medial talar cartilage lesions.⁵ Taga et al. found the incidence of talar cartilage damage in those with CAI to be as high as 95%.¹⁹ Increased stress distribution on the medial aspect of the ankle joint has also been shown in this population and is hypothesized to contribute to cartilage damage.⁵ Cartilage damage as a result of ankle sprains/CAI has been related to the development of post-traumatic osteoarthritis regardless of initial injury severity.⁶ Given these long-term consequences that effect quality of life, addressing CAI should be a priority for clinicians. In order to manage CAI, an understanding of the mechanism driving the instability is crucial. One of the major contributing factors to CAI is adaptation to the sensorimotor system.

Sensorimotor Adaptations

Mechanical and/or functional instability contribute to CAI development;²⁰ where mechanical instability refers to physical changes to static stabilizers of the ankle joint which include ligaments, joint capsule, cartilage, and bony geometry.²⁰ Long after the initial injury, functional deficits remain that cannot be explained by increased laxity or dysfunction of static ankle joint stabilizers.⁹ This is referred to as functional instability and is often attributed to sensorimotor system dysfunction.²¹ The sensorimotor system is a complex subcomponent of the motor control system in the body.²² This system is responsible for maintaining dynamic joint stability through central integration and processing of the sensory and motor systems.²² The sensory contribution involves integration and processing of visual, vestibular, and somatosensory inputs.²² The visual component consists of the reception and processing of visual information and will be

discussed in further detail later on in this chapter. The vestibular component contributes information regarding the position of the head in respect to gravity.²³ The somatosensory system is composed of a network of peripheral sensory receptors.²² Broadly defined as mechanoreceptors, they are subcategorized by their location and thus include tenomuscular (tendon and muscle), articular (ligaments and joint capsule), cutaneous receptors (skin).²² Tenomuscular receptors are sensitive to changes in muscle length and tension.²² Articular receptors are sensitive to joint position, displacement, stress, and velocity.²² Cutaneous receptors are sensitive to touch, pressure, pain, and temperature.²² Accurate information from all three systems is crucial in anticipating and formulating the correct motor response to internal or external perturbations in order to maintain stability.²²

The motor contribution to the sensorimotor system includes the motor output dictated by sensory input²² in order to maintain joint equilibrium. Motor output can be subcategorized into feedforward and feedback responses.²² Feedforward indicating anticipatory muscle activation stemming from previous experience and sensory information.²² Feedback indicating reactive or reflexive muscle activity to internal or external perturbations, determined by input from sensory receptors.²² Appropriate motor response is essential in producing movements that prevent unfavorable joint positions that could result in tissue damage. Alterations in either sensory input or motor output can decrease joint stability and predispose an individual to injury. Function of the sensorimotor system has been thoroughly examined in the CAI.²⁴⁻²⁹ Those with CAI have been shown to have alterations in the sensorimotor system that arise after the initial injury and persist past healing.^{25,26,28,29}

Function of the somatosensory system has been assessed in the CAI population.^{10,25,27,30,31} Docherty and Arnold found that CAI patients had a decreased ability to replicate a given eversion force, indicating dysfunction of articular receptors responsible for sensing joint force.³¹ Other studies have shown more evidence of articular receptor dysfunction in CAI patients through a decreased ability to reproduce a given joint position.^{32,33} Cutaneous receptor function has been assessed using Semmes Weinstein Monofilaments to measure cutaneous sensation threshold in the ankle and foot complex.²⁷ The CAI population has been shown to have higher light-touch cutaneous sensation thresholds in the foot and ankle complex compared to healthy controls.^{27,34} Vibratory perception threshold, measured with a handheld biothesiometer, has also been used to assess the function of cutaneous receptors in CAI patients.^{25,35} In the CAI population, plantar cutaneous vibratory perception threshold has been shown to be higher compared to controls, including at 1st and 5th metatarsal sites, similar to monofilament findings above.^{25,36} Deficits in joint force and position sense along with higher light touch and vibratory thresholds indicate poor somatosensation^{25,35} and therefore indicate an altered sensorimotor system, leading to potential for injury via inadequate joint stability.

Adaptations to the motor response component of the sensorimotor system have also been reported in the CAI population.³⁷ Commonly, muscle weakness, muscle inhibition, and abnormal movement patterns are associated with CAI.⁹ Adaptations of the Hoffmann's reflex (H-reflex) at both the spinal and supra-spinal levels seen in CAI patients can help explain these findings.^{28,29,38} The H-reflex is an electrically stimulated analogue to the mechanically stimulated stretch reflex and represents a muscle's alpha

motorneuron pool excitability.^{28,38} Those with CAI have been found to have a depressed H-reflex in the soleus and peroneal muscles of the involved limb, indicating decreased muscle activation capacity.³⁷ This spinal-level adaptation, often referred to as arthrogenic muscle inhibition, is thought to be a consequence of the initial injury.³⁷ Upon initial injury, inflammation, pain, and altered sensory output inhibit muscles around the affected joint.²² Arthrogenic muscle inhibition of the soleus and peroneal muscles is thought to result in muscle weakness and motor activation alteration in the CAI population.³⁷ A study by Bowker et al. agreed with previous evidence³⁷ and found decreased H-reflex excitability in the soleus of CAI patients compared to copers, but no difference in mechanical laxity between the two groups.³⁹ This finding indicates that mechanical laxity may not play a major role in the sensorimotor adaptations seen in CAI patients.³⁹ The soleus and peroneal muscles play an important role in maintaining dynamic joint stability at the ankle.²⁹ Therefore, motor dysfunction in these muscles may increase risk of reinjury.

In healthy individuals, it has been shown that the H-reflex is reduced or down-modulated with increasingly complex postural tasks.^{28,29} It is hypothesized that the H-reflex is down-modulated during these tasks in order to shift motor-control from spinal to supra-spinal levels.²⁸ This shift to supra-spinal centers allows for finer control of increasingly complex postural tasks.²⁸ In the CAI population however, altered modulation of the H-reflex has been found in the soleus and peroneal muscles of the involved limb during increasingly complex postural tasks, indicating decreased cortical control.^{28,29} Decreased cortical control during a complex task would decrease the individual's ability to make fine motor adjustments and result in predisposition to

injury. Measuring the magnitude of motor-related cortical potentials (MRCP) with EEG is one way to determine the extent to which cortical resources are required to maintain stability. A study by Burcal et. al. saw increased MRCPs in the CAI population during leaning tasks, especially when leaning toward the involved limb, indicating increased cortical resources necessary and less automatic ability to maintain postural control.⁴⁰

Other post injury cortical level adaptations include altered working memory capacity—short-term memory associated with immediate perceptual processing. This was observed in those with ligamentous injury to the ACL; though evidence in the CAI population is lacking.⁴¹ Alterations in working memory may affect the feedback mechanism used to maintain postural control⁹ due to its role in determining appropriate action based on perception. The combination of reduced H-reflex excitability, altered modulation of the H-reflex, decreased working memory capacity predisposes the individual to postural control deficits and, therefore, risk of reinjury.

Postural Control Deficits

The sensorimotor system is responsible for maintaining postural control, as described above. Postural control, or balance, broadly refers to the ability to maintain stability of the body and its segments through anticipatory and reactive motor responses.^{23,42} Postural control is essential in both static and dynamic circumstances to prevent movement that may cause injury.²³ Impaired postural control, therefore, presents a concern. Deficits in postural control have been exhibited in the CAI population.⁴³ These deficits have been shown as worse postural control outcomes in laboratory settings and decreased performance on clinical balance assessments.^{26,44}

In the laboratory, time-to-boundary (TTB) —a force plate measurement that determines the time it would take for the center of pressure (COP) to leave the boundaries of the base of support if it continued at the same velocity and direction—is one way of evaluating postural control.⁴⁵ A shorter TTB indicates that an individual's sensorimotor system would have less time to make a postural adjustment before the COP leaves the boundaries of the base of support.⁴⁶ McKeon et. al. showed that individuals with CAI, regardless of sex, have significantly shorter TTB under eyes-closed conditions than healthy controls, indicating decreased postural stability.⁴³

The Balance Error Scoring System is a simple, clinically-based tool used to assess balance deficits and has been used in the CAI population.²⁶ During various stance conditions, balance errors are subjectively measured, more balance errors indicate worse postural control.²⁶ Powell et al. found those with CAI had higher balance error scores under both firm and foam conditions.²⁷ The Star Excursion Balance Test is another clinically-based assessment tool that requires the patient to stand on one limb and reach as far as possible in 1 of 8 directions with the other limb.²⁶ The reach distance is measured and farther distances indicate better postural control.²⁶ Those with CAI have been shown to have lower SEBT scores indicating worse postural controls compared to healthy individuals.^{44,46}

Impaired postural control could be explained by the multifaceted dysfunction of the sensorimotor system described above. Formerly mentioned neuromuscular adaptations as well as somatosensory and motor cortex alterations may play a role in postural control deficits seen in CAI.

Sensory Reweighting Compensation

The exact cause of the sensorimotor system adaptations mentioned above that result in postural control deficits in CAI patients is not fully understood. One theory, derived mainly from ACL research, involves evidence of reorganization, or neuroplasticity, of higher level integration centers.^{9,11} It is hypothesized that initial ligamentous injury leads to damaged mechanoreceptors in the tendinous and capsuloligamentous structures in the area, which would subsequently alter the sensory information that is being transmitted to the spinal cord/brain about joint position and joint movement.⁹⁻¹¹ This consequence, often referred to as peripheral deafferentation,⁹ along with pain and inflammation associated with the initial injury, disrupt sensory feedback to the brain.⁹ Neuroplasticity of the somatosensory cortex is a possible consequence of the interruption of once continuous sensory input.⁹ Neuroplasticity of the somatosensory cortex has been shown by measuring somatosensory-evoked potentials (SEPs) using electroencephalography (EEG).⁹ Studies have provided evidence that while the somatosensory-evoked potentials from the involved region may reach the spinal cord, they may not reach the somatosensory cortex in those with ligamentous injury.⁹ Neuroplasticity of the motor cortex, evidenced by changes in excitability of descending cortical pathways,²⁴ could be a potential result of changes to the somatosensory cortex.⁹ To review, appropriate selection of motor output requires the integration of sensory inputs from the visual, vestibular, and somatosensory in order to maintain postural control. However, the use of these three systems by the brain is not uniform and is reweighted depending on the the health of the individual, demands of the task, and the affordance of the environment.^{23,47} In order to compensate for reduced

somatosensory input in ligamentous injuries, the highly adaptive central nervous system increases the use of visual feedback for motor processing.⁹ With altered input from the somatosensory cortex, the motor cortex would be forced to adopt a new strategy of obtaining sufficient information to produce appropriate motor response.^{9,11,23} Over time, it is thought that the motor control system relies on the visual component of the sensorimotor system in order to maintain postural control.¹¹

Information is lacking regarding the sensory organization strategies of the CAI population, but it appears in emerging literature to involve this compensation of sensory reweighting to the visual system.^{12,43,48} A recent systematic review with meta-analysis¹⁵ evaluated studies that compared postural control outcomes during eyes-open and eyes-closed conditions to evaluate the ability to reweight somatosensory information in the absence of visual information in those with CAI and healthy controls. Results of this study showed that compared to healthy controls, the magnitude of postural control declines were significantly worse in eyes-closed conditions relative to the eyes-open condition, indicating a reduced ability to reweight sensory information and therefore an increased reliance on visual information to maintain postural control in single limb stance.¹² This provides evidence that the initial compensation of sensory reweighting to visual information remains after healing and leads to visual reliance in those with CAI.¹²

Lasting alteration of the somatosensory cortex from the initial injury may be an underlying issue. Those with CAI have been shown to have alterations to the somatosensory cortex after injury healing.⁴⁹ Needle et al. investigated activation of the somatosensory and motor cortices during ankle joint loading in healthy controls,

copers, and CAI.⁴⁹ They found that while the somatosensory and motor cortices were active in all groups during joint loading, these measures in the CAI group increased in the initial phase of loading but did not increase with joint load.⁴⁹ This finding indicates that while the somatosensory and motor cortices may receive information about the presence of joint loading, information about the magnitude of the load is not perceived.⁴⁹ The continued disruption of accurate somatosensory information to the motor control system may be the cause of the continued visual reliance, even after joint mechanoreceptors are healed. In essence, the message sent from somatosensory receptors may not be received by the brain (absence of SEPs), or may only be received in part (increase in activity of somatosensory cortex during initial phase of loading only) causing changes to the system.^{9,49}

Determination of whether visual reliance is a positive or negative adaptation has not been reached. On the one hand, reliance on visual information could have negative effects. The inability to reweight the sensory system to integrate somatosensory information when visual information is absent could predispose the individual to injury due to impaired postural control.^{23,47} The individual's sensorimotor system fails to benefit from unintegrated sensory information, unless this information is faulty in nature. Assuming that somatosensory receptors, themselves, are capable of transmitting accurate sensory information once they are healed, this information would serve to benefit the sensorimotor system, especially when visual input is disrupted. The question remains if it is possible to reverse the neuroplasticity of the somatosensory cortex that potentially lead to the reliance of visual information after initial ligamentous injury. Further research in this area is required. Reliance on visual information to

maintain posture could place a burden on visual processing power during complex motor and cognitive tasks such as participating in sport. Poor visual processing speed and reaction time have been shown to be risk factors in ACL injury, indicating that decreased visual processing ability already predisposes the individual to injury without the added demand resulting from visual reliance.¹¹ This may leave the individual predisposed to injury as there may not be “enough visual resources to go around”. This way of thinking would lead to the conclusion that developing methods of training sensory reweighting to incorporate somatosensory input and decrease visual reliance are important and necessary.

Conversely, visual reliance may not be a negative adaptation. Recovery of normal somatosensory cortex function and information integration may not be possible (evidenced by failure of balance training to alter visual reliance)¹⁵. In this case, reliance on visual information may be a necessary adaptation to maintain postural control. Without the adaptation of visual reliance, sensory information sufficient enough to produce accurate motor response may not be available. The individual may positively adapt to a higher demand placed on visual resources. If somatosensory information is not to be trusted—if somatosensory receptors themselves are dysfunctional—incorporating this information may be more detrimental than ignoring it. In this case, it could be concluded that improving visual processing capacity is necessary for CAI patients to allow the affordance of higher demand placed on this system.

Visual reliance, good or bad, is an important factor for the clinician to take into account as it is prevalent in the CAI population and is not addressed through traditional balance training programs.¹⁵

Current Treatment Methods

Functional rehabilitation has been shown to be one of the most important aspects of managing an ankle sprain and reducing postural control deficits.⁵⁰ These programs typically follow a period of immobilization and activity restriction⁵¹ complimented with rest, ice, compression, and elevation and non-steroidal anti-inflammatory drugs.⁵² Balance training is a central component of CAI rehabilitation with goals of strengthening surrounding musculature and improve postural control.^{46,53} Balance training usually consists of a progression from wide to narrow base of support, firm to unstable surface, and eyes-open to eyes-closed tasks.^{13,14} These balance programs have been shown to improve patient-reported and postural control outcomes in those with CAI.^{46,54} One study reported a decrease of 60% in patient reported episodes of “giving way” one year after completing a six week balance and coordination program.⁵⁵ McKeon et al. found increased (ie improved) TTB in eyes-closed static single-limb stance in those with CAI following a 4 week balance training program.⁴⁶ Improvement in balance tasks is often attributed to improvement of proprioception,¹⁴ however, it has yet to be supported that true measures of proprioception, such as joint position sense and passive joint movement detection threshold, are improved through balance training.¹⁴ Improvements following balance training in those with CAI are often attributed to better organization of the sensorimotor system and better proprioception.^{14,46} However, recent meta-analysis has found that even after balance training, those with CAI remain visually reliant¹⁵ indicating a lack of sensory reorganization. The underlying reason for these improvements remains unclear. Given that poor postural control is a risk factor for recurrent lateral ankle sprains^{20,56} and that

those with CAI rely more heavily on visual information to maintain postural control,¹² determining if there is a relationship between visual and somatosensory performance, the integration of these systems, and postural response to altered visual information is key to understanding the role of visual reliance in those with CAI.

Vision

Visual Contribution to Postural Control

In order to understand the role of vision in those with CAI, it is important to first understand the function of vision in healthy human postural control and locomotion. Vision is an essential source of information used in planning and producing stable, purposeful movement.⁵⁷ Before it can be processed, visual information must be received from various receptors (i.e. the retina).⁵⁸ From this information, only the most relevant—largely determined by past experience—is selected for further processing.⁵⁸ Two modes of visual processing have been identified: focal and ambient. The focal mode of vision answers the question of “what?” about an object and registers events primarily in the central retina.⁵⁹ Ambient vision answers the question of “where?” about both an object’s location relative to the observer and the observer’s location relative to the environment.⁵⁹ It functions primarily in the periphery and registers low spatial frequencies in a large area of the visual field⁵⁹. Ambient vision, therefore, is essential in the maintenance of postural stability and works in conjunction with the somatosensory and vestibular systems to provide accurate sensory information to the motor control system.⁶⁰ After pertinent information is selected, the decision mechanism decides what action is required and selects a response based on prior experience and expectations.⁵⁸ In the situation of postural control, the action required is a motor response. In this case,

the effector mechanism organizes the aspects of the desired movement and produces a neural command which travels to the specified muscle groups and produces a contraction with the magnitude of force and time indicated by the effector mechanism.⁵⁸ Improving visual processing would therefore benefit the sensorimotor system by providing accurate and timely information about the environment. Steps to improving the visual processing system begin with assessing its current function and performance.

Assessing Visual Function and Performance

Visual function refers to the capacity of the visual sensory organs to receive information⁵⁸ and influences both focal and ambient modes of visual processing.^{58,59} Measures of visual acuity, depth perception, ocular muscle balance, color vision, contrast sensitivity, and peripheral visual range are examples of visual function that are commonly assessed.⁵⁸ Assessments of visual acuity, or sharpness of vision, such as the Snellen Eye Chart and the Early Treatment of Diabetic Retinopathy Chart are frequently administered because they are simple and cost effective. Other charts and instruments have been developed to assess contrast sensitivity (Pelli-Robson Chart), color vision (Ishihara 38 Plates CVD Test), and peripheral visual range (kinetic perimetry). More comprehensive tools of assessing many aspects of visual function have been developed such as the Senaptec Sensory Station, which assesses many aspects of visual function using an interactive computerized system.

Visual performance often refers to how well the individual is able to process and respond to visual information.⁵⁸ This involves proper extraction of relevant information, retrieval of perceptual information from memory, and ability to maintain

appropriate attentional focus to avoid processing of irrelevant visual information.⁵⁸

Assessing visual performance is often done by measuring visual-motor reaction time with tasks that require the reception and processing of visual information dictating a motor response. An example of this might be a task such as spotting a visual queue in the periphery and quickly reaching to touch it, which would evaluate hand-eye-coordination as well as peripheral field view. It is unclear whether visual function can be improved through training programs, however there is evidence that visual processing can be improved.⁵⁸

Improving Visual Performance and Stroboscopic Goggles

There is great interest in the ability to improve visual performance as it has broad applications as a range of populations could seek to benefit from improvement. For example, deterioration in visual performance is thought to be a contributing factor to automobile crashes in elderly population.⁶¹ Higher level athletes have been found to have better visual processing abilities.⁵⁸ For the purpose of this study, ability to improve visual performance could function to improve postural stability in those with CAI who are visually reliant.

There is evidence that visual training improves visual performance.⁵⁸ Recent interest in this area has developed with the use of stroboscopic goggles to improve visual processing performance. Strobe glasses intermittently flash between transparent and opaque lenses with the option to adjust the frequency of transitions in one or both lenses.⁶² They have been shown to improve anticipatory timing⁶³ and short-term memory,⁶⁴ and enhance visual cognition.⁶⁵ Besides their ability to better visual

processing performance, the use of these goggles has been used in recent research to evaluate the sensorimotor system.⁶⁶

One recent study showed stroboscopic visual conditions had the same disruptive effect on postural control measures as eyes-closed conditions in healthy individuals in single-limb stance on a foam pad.¹⁶ This indicates that during a disruption to the somatosensory system (i.e. foam pad), even a partial obstruction of visual information may lead to an impairment of postural stability such as that under eyes-closed conditions.¹⁶ This has important implications for individuals with CAI as they have greater reliance on visual information and downregulate the use of somatosensory information to maintain postural control compared to healthy controls.¹² Balance training does not improve visual reliance.¹⁵ This could leave the CAI population vulnerable to injury during activities that require high levels of visual attention on the environment, potentially leaving less cognitive resources available to neuromuscular control.¹¹ However, if using stroboscopic eyewear is as effective in disrupting visual input as eyes-closed conditions, this tool has potential to train sensory reweighting with dynamic exercises, previously infeasible due to potential hazards. Dynamic exercises completed under eyes-closed conditions present the danger of being unaware of one's surroundings; stroboscopic eyewear would allow enough visual information to avoid obstacles while stressing the sensorimotor system as effectively as eyes-closed conditions. This type of training may improve the efficiency of the sensorimotor system when visual information is less available. If training sensory reweighting is not effective, stroboscopic vision training may still benefit those with CAI as it could improve function of the visual processing system.

Limited evidence exists surrounding the effect of varying levels of visual occlusion on postural control measures in either healthy or CAI populations. Determining the postural control response to levels of visual occlusion can help determine if using limited vision conditions (strobe goggles) in place of no vision conditions (eyes-closed) in balance training provides the same stress to the sensorimotor system with the added capability of performing functional tasks. Also limited is our understanding of the influence of visual and function and performance and the sensory integration strategy in CAI patients on postural control measures during varying levels of visual occlusion. This information could provide a broader understanding of the role of these sensory inputs in postural control under varying visual conditions. This study aims to expand the information in these areas.

CHAPTER III: METHODS

Study Design

This quasi-experimental cross-sectional study was approved by the university's institutional review board and performed in a clinical research center. Participants completed one 2-hour long testing session including visual performance, sensory integration, and balance testing as part of a larger study. Visual performance was assessed using the Senaptec Sensory Station battery. Sensory integration was assessed using the Sensory Organization Test. Finally, an assessment of postural control was completed involving double-limb balance on a triaxial forceplate under varying levels of visual input produced by stroboscopic eyewear.

Participants

Fifty-one participants (15 males (29.4%); age=21.1±2.0 years; mass=66.2±10.7 kg; height=1.7±0.1 m) participating in a larger study provided written informed consent and were included presently. All participants qualified as having CAI according to the International Ankle Consortium inclusion criteria recommendations². All participants were physically active, defined as completing moderate to vigorous activity at least 3 times per week for at least 30 minutes during the past 3 months. **Table 1** outlines participant demographic information. Recruitment of participants within the university population was accomplished by email or in person.

Visual Performance

The Senaptec Sensory Station (Senaptec, Beaverton, Oregon) was used to assess visual function, processing, and performance. The system consists of two touch-sensitive, high resolution liquid crystal monitors (22-inch and 42-inch) controlled by a single computer and a Motorola Moto G3 smartphone (Motorola Mobility, LLC, Schaumburg, IL) used remotely to register participant responses to the Senaptec system assessments. The Senaptec Sensory Station assessment takes approximately 25 minutes to complete and includes a battery of 10 tests: visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple object tracking, hand-reaction time, target capture, hand-eye-coordination, and go-no-go. Participants were provided verbal instruction on, a demonstration of, and allowed to practice prior to completing each test. **Table 4** provides a detailed explanation for each test and describes the outcomes of interest that served as our independent variables. The Senaptec Sensory Station is the successor to a comparable computer-based system (Nike Sensory Station) of which these series of visual function and performance tests have been found reliable.⁶⁷

Sensory Integration

Sensory integration was evaluated using the Sensory Organization Test (SOT) of the SMART Balance Master (NeuroCom International, Clackamas, OR). The SOT measures dynamic posturography using two 9 X 18 inch force plates under 6 conditions designed to alter the visual, vestibular, and visual sensory systems: 1) eyes open, stationary support surface, 2) eyes closed, stationary support surface, 3) eyes open, sway-referenced visual input with stationary support surface, 4) eyes open with sway-

referenced support surface, 5) eyes closed with sway-referenced support surface, and 6) eyes open, with sway-referenced visual and support surface. Each condition is repeated 3 times for a total of eighteen, 20 second trials. Participants stood without shoes on the system's forceplates in double-limb support (DLS). Foot placement was adjusted per system requirements, and was readjusted if movement during the trial occurred. Participants were instructed to stand as still as possible with their arms at their sides and remain quiet throughout the trials. The first 6 trials were completed in order of conditions 1-6 to acclimate the participant to the test. The next 6 trials began with condition 1, followed by condition 2, followed by conditions 3-6 in an operator-randomized order. The last 6 trials were randomized by the operator. SOT procedures have been thoroughly detailed in previous work.⁶⁸

Equilibrium scores for each trial were computed based on an algorithm developed for the SMART Balance Master and used to calculate an overall composite score and three ratio scores (vestibular, visual, and somatosensory) for each participant. The composite score represents the weighted average sway across all testing conditions. Better postural control is indicated by a higher composite score.⁶⁸ The ratio scores represent the individual's ability to use the specified sensory system to maintain balance when the other two systems are unavailable or altered, and also served as independent variables.⁶⁸ Vestibular, visual, and somatosensory ratio scores are calculated by comparing select conditions (5, 4, and 2 respectively) to the reference condition (1) in which all sensory systems are available and unaltered. Higher ratio scores represent better ability to integrate information for the specific sensory system⁶⁸.

Postural Control

A triaxial forceplate (AMTI, Watertown, MA) was used to examine postural control by recording center-of-pressure (COP) measurements at a sampling frequency of 100Hz via Balance Clinic software (version 2.02.01). A Matlab software program (MathWorks, Inc., Natick, MA, USA) was used to compute the postural control outcomes. Low (level 2) and high (level 6) visual occlusion conditions were produced using Senaptec Strobe Training Goggles (Senaptec, Beaverton, OR). Participants completed a 3-minute trial in DLS under four visual conditions: 1) eyes-open, 2) low-occlusion, 3) high-occlusion, and 4) eyes-closed. Participants were instructed to stand still with arms at side and focus on a self-selected point on the wall in front of them. Foot placement was preserved between trials to ensure consistency.^{69,70}

Time-to-boundary mean of minima in the mediolateral (TTB-ML) and anteroposterior (TTB-AP) directions served as dependent variables in this study. Previously described by Hertel et al⁷⁰, TTB ML and TTB AP are calculated in seconds using COP excursion velocity and moments as well as the dimensions of the individual's base-of-support. TTB is an estimate of the time a person has before their COP would extend past the base of support, resulting in balance loss, if a postural correction is not made.⁷⁰ Therefore, a shorter TTB indicate worse postural control.⁷¹ TTB mean of minima has been shown to be a reliable measure of postural control (ICC=0.62-0.87).⁷⁰ This measure is commonly used in this field of study because it has greater sensitivity to postural control differences between the CAI population and healthy controls compared to other center-of-pressure measures that do not consider boundaries of stability.^{69,72} After sampling, forceplate data were converted to digital format and stored

on a personal laptop with data acquisition and data-analyses software. Original forceplate COP data were processed with a fourth order, zero-lag, low-pass Butterworth filter with a cutoff frequency of 5 Hz.^{43,69,72} Data from the 1st minute of each trial acted as four 15-second trials to allow better congruence with previous methodology in this field.^{12,44} Due to a limited sample size, TTB AP and TTB ML outliers—defined as falling outside 2 standard deviations above or below the mean—were adjusted by averaging the preceding two extreme values.

Statistical Analysis

For all aims, continuous clinical variables are summarized as mean \pm standard deviation and categorical variables are presented as frequencies and corresponding percentages.

Aim 1: Two-way repeated measures ANOVAs were used to assess differences between groups (CAI vs. healthy) and visual conditions (eyes-open, low-occlusion, high-occlusion, and eyes-closed) on TTB AP/ML minima means using statistical software (SAS 9.4).

Aim 2: Initial univariable regressions were computed to evaluate individual relationships between the 10 Senaptec subtest's and postural control outcomes (TTB AP/ML mean of minimas) under the eyes-open and limited conditions. Univariable relationships that demonstrated a p-value of $p \leq 0.1$ were considered for inclusion in the stepwise models. Two stepwise multivariable regressions (eyes-open and limited conditions) were calculated to examine the influence of visual system performance measures on postural control outcomes under varying levels of visual occlusion in those with CAI. Sequence of input into the greater models was determined based on the

Senaptec variables that demonstrated the greatest relationship with each dependent variable separately.

Aim 3: To test the influence of individual sensory system integration capability on postural control under eyes-open and limited-visual conditions in those with CAI, four multivariable regressions were calculated (two conditions, two dependent variables). Visual, vestibular, and somatosensory ratio scores were put into the models consistently in that order. A priori alpha level was set to $p=0.05$.

Table 1. Demographic information by group. Mean (SD)

	Healthy (n=16)	CAI (n=35)
Sex		
Male	6	9
Female	10	26
Age (y)	21.1 (2.2)	21.1 (1.9)
Height (m)	1.72 (0.1)	1.70 (0.1)
Mass (kg)	66.1 (11.7)	65.9 (10.3)
Number of Ankle Sprains	0 (0)	3.7 (2.2)
Episodes of Giving Way (past 3 mo.)	0 (0)	3.3 (3.6)
FAAM-ADL (%)	100 (0)	89 (10)
FAAM-Sport (%)	100 (0)	80 (15)

FAAM-ADL= Functional Ankle Ability Measure of Activities of Daily Living. FAAM-Sport= Functional Ankle Ability Measure of Sport related activities.

Table 2. Average postural control outcomes for healthy (n=16) and CAI (n=35) groups by visual condition. Mean (SD)

	TTB AP (s)		TTB ML (s)	
	Healthy	CAI	Healthy	CAI
Eyes open	30.3 (7.7)	28.9 (6.1)	64.9 (24.5)	64.5 (17.5)
Low occlusion	22.3 (6.8)	21.2 (7.7)	56.2 (22.7)	53.9 (20.9)
High occlusion	24.1 (4.1)	21.2 (6.6)	55.5 (20.5)	56.0 (18.6)
Eyes closed	19.0 (5.6)	19.6 (5.5)	48.2 (16.0)	53.9 (15.6)

TTB AP=time-to-boundary in the anterior-to-posterior direction. TTB ML= time-to-boundary in the medial-to-lateral direction.

Table 3. Average time-to-boundary under various levels of visual occlusion with effect size, collapsed across group. Mean (SD)

	TTB AP (s)	TTB ML (s)
Eyes Open (EO)	29.3 (6.6)	64.7 (19.7)
Low Occlusion (LO)	21.5 (7.4)	54.6 (21.3)
High Occlusion (HO)	22.1 (6.1)	55.9 (19.0)
Eyes Closed (EC)	19.4 (5.5)	52.1 (15.8)
Effect Size (upper bound, lower bound)		
EO-LO	-1.47 (-1.91, -1.04)*	-0.79 (-1.19, -0.39)
EO-HO	-1.46 (-1.90, -1.02)*	-0.66 (-1.06, -0.26)
EO-EC	-1.81 (-2.27, -1.35)*	-0.95 (-1.36, -0.54)*

*Represents a significant ($p \leq 0.05$) effect size. TTB AP=time-to-boundary in the anterior-to-posterior direction. TTB ML= time-to-boundary in the medial-to-lateral direction.

Table 4. Senaptec Sensory System Test detailed outcomes and procedures.

Test	Meaning of Score	Description	Procedures
Visual Clarity (VC)	Lower=better	How clearly one sees distant details, measured in LogMAR.	Black Landolt rings (C-shaped ring) with openings at the top, bottom, left, or right appeared in random order on a white background. The participant is instructed to swipe the screen of the remote input device in the direction of the opening of the Landolt ring. The rings are preset at varying acuity demands. The procedures include monocular assessments followed by a binocular assessment.
Contrast Sensitivity (CS6, CS18)*	Lower=better	Ability to pinpoint subtle differences in contrast. Measured as Log CS= -log/threshold	Four black circles are presented on a light background. At random, one of the circles will contain a pattern of rings. The participant is instructed to swipe the screen of the remote input device in the direction of this circle.
Depth Perception (DPf, DPl, DPr)	Lower=better	Accuracy in judging 2-eyed depth information through multiple gaze positions. Measured in arcseconds.	The 3D glasses simulate depth in one of the four rings that appear on the screen. The participant is instructed to swipe the screen of the remote input device in the direction of the ring that appears closest. Test procedures are repeated standing to the side looking over both left and right shoulders.
Near-Far Quickness (NFQ)	Higher=better	Ability to quickly & accurately change visual attention between near and far distances. Measured as number of completed cycles.	A series of black Landolt rings appear, alternating between the remote input device screen and the screen on the tablet display. The participant is instructed to swipe the screen of the remote input device in the direction of the opening of the Landolt ring.
Perception Span (PS)	Higher=better	Speed and accuracy in obtaining critical visual information. Measured as number of correctly identified circles.	The participant focuses on a dot in the center of a grid pattern composed of up to 30 circles. A pattern of dots flash within the grid. The participant then attempts to replicate the pattern on the tablet screen.
Multiple Object Tracking (MOT)	Higher=better	Accuracy in tracking multiple objects moving at varying speeds. Measured as number of correctly identified circles minus the number of those misidentified.	The participant focuses on a central point of the screen. Two to five sets of circles appear on the tablet screen. One dot of each pair briefly flashes red. The dots then rotate around each other at varying speeds. Once the dots are immobile, the participant is instructed to select the dot in each pair that flashed red at the beginning of the test.
Reaction Time (RTavg, RTd, RTnd)	Lower=better	Duration of time it takes an individual to accurately respond to a visual stimulus with their hand. Measured in msec.	Two annular patterns appear on the screen. The participant places their index fingers on the inner circle of each pattern, and focuses on the center of the annular pattern in front of them. After a random delay of 2, 3, or 4s, one or both patterns turn red, prompting the athlete to remove the required index finger(s) as quickly as possible.

Target Capture (TC)	Lower=better	Ability to shift visual attention and recognize peripheral targets. Threshold reached measured in msec.	The participant focuses on a central black dot until a Landolt ring appears briefly in one of the corners on Senaptec Sensory Station display. The participant is instructed to swipe in the direction of the opening of the Landolt ring.
Eye-Hand Coordination (EHC)	Lower=better	Ability to make quick and accurate visually-guided hand responses to rapidly changing targets. Total time to complete test, measured in msec.	A grid is presented with ten columns and eight rows of equally sized and spaced circles. A green dot appears within one circle of the grid. Participant is instructed to touch the dot as quickly as possible with either hand. As soon as they touch the dot, another dot will be presented. 80 dots will appear.
Go/No-Go (GNG)	Higher=better	Ability to make quick and accurate decision responses to rapidly changing targets. Measured as (total green dots hit plus 0.25*total green dots hit within 0.5 seconds of disappearing) minus (total red dots hit plus 0.25*red dots within 0.5 seconds of disappearing).	An identical grid as Eye-Hand Coordination test appears. A green or red dot will appear. If the dot is green, the participant is instructed to touch it. If the dot is red, the participant is instructed not to touch it. Eighty dots will appear in a pseudorandomized sequence.

For VC, CS, DP, NFQ, and TC subtests, participants stood 10 ft from tablet, holding remote input device. For PS, MOT, and RT subtests participants stood 2 ft from and responded on tablet. For EHC and GNG subtests, participants stood 2 ft from and responded on 42-in display. Contrast Sensitivity was measured at two frequencies, 6 and 18 cpm.

Table 5. Average Senaptec Sensory System and Sensory Organization Test outcomes. Mean (SD).

Sensory Organization Test Outcome	Outcome
Visual Ratio Score	83.4 (13.1)
Vestibular Ratio Score	71.4 (14.5)
Somatosensory Ratio Score	97.5 (2.92)
Comprehensive Score	75.6 (9.7)
Senaptec Sensory Station Outcomes	
Visual Clarity	-0.13 (0.12)
Contrast Sensitivity at 6 cpm	2.0 (0.1)
Contrast Sensitivity at 18 cpm	1.6 (0.3)
Depth Perception (forward-facing)	129.2 (94.2)
Depth Perception (left-facing)	154.7 (89.2)
Depth Perception (right-facing)	142.4 (92.1)
Near-Far Quickness Score	25.2 (4.8)
Target Capture	180.3 (66.2)
Perception Span	45.7 (11.4)
Multiple Object Tracking	1729.6 (451.6)
Eye-Hand Coordination	55.5 (27.7)
Go/No-Go	20.3 (6.1)
Reaction Time	324.6 (30.1)
Reaction Time (dominant hand)	322.5 (31.4)
Reaction Time (non-dominant hand)	326.2 (33.0)

Table 6. Univariable analyses of Senaptec variables included in the time-to-boundary anterior-to-posterior stepwise model.

Condition	Senaptec Variable	Estimate	95% CI		<i>P</i>
Eyes-open	VC B	15.25	-2.85	33.35	0.096
	PS	0.23	0.05	0.42	0.013
	RT D	-0.06	-0.13	0.004	0.065
Limited-vision	VC B	15.94	-2.21	34.10	0.083
	TC	-0.03	-0.06	0.005	0.091
	PS	0.23	0.05	0.41	0.016
	EHC	<0.01	-0.00001	0.0001	0.096

Only Senaptec outcomes that demonstrated adequate significance ($p < 0.10$) are included in this table.

Table 7. Univariable analyses of Senaptec variables included in the time-to-boundary medial-to-lateral stepwise model.

Condition	Senaptec Variable	Estimate	95% CI		<i>P</i>
Eyes open	DP R	-0.06	-0.13	0.006	0.072
	TC	-0.10	-0.19	-0.01	0.028
	PS	0.78	0.30	1.27	0.002
	EHC	<0.01	0.000006	0.0004	0.045
Limited vision	TC	-0.08	-0.17	0.01	0.080
	PS	0.63	0.13	1.13	0.015

Only Senaptec outcomes that demonstrated adequate significance ($p > 0.10$) are included in this table.

Table 8. Stepwise multivariable regression analysis for time-to-boundary anterior-to-posterior outcomes under both eyes-open and limited-vision conditions

Condition	Predictor	Estimate	R ²	ΔR ²	<i>P</i>
Eyes open	Intercept	18.3	-	-	<0.001
	PS	0.23	0.18	-	0.013
Limited vision	Intercept	10.1	-	-	0.024
	PS	0.23	0.17	-	0.016

Table 9. Stepwise multivariable regression analysis for time-to-boundary medial-to-lateral outcomes under both eyes-open and limited-vision conditions

Condition	Factor	Estimate	R ²	ΔR^2	<i>P</i>
Eyes open	Intercept	47.15	-	-	<0.001
	PS	0.76	0.18	-	0.002
	TC	-0.10	0.39	0.21	0.016
Limited vision	Intercept	10.1	-	-	0.034
	PS	0.63	0.18	-	0.015

CHAPTER IV

Overview

Those with chronic ankle instability (CAI) are often described as visually reliant due to postural control deficits observed under fully occluded visual conditions. Little is known about the influence of partially occluded vision on postural control in those with CAI.

To examine differences in postural control in those with and without CAI under increasing levels of visual occlusion during static stance compared to eyes-open.

Thirty-five participants with CAI and sixteen participants with no history of lower extremity injury completed four 3-minute postural control assessments in double-limb stance on a triaxial forceplate under the following four visual conditions: 1) eyes-open, 2) low-occlusion, 3) high-occlusion, and 4) eyes-closed. Low (level 2) and high (level 6) occlusion conditions were produced using stroboscopic eyewear. Postural control outcomes included time-to-boundary minima means in the anteroposterior (TTB-AP) and mediolateral (TTB-ML) directions, calculated from forceplate data. Two-way repeated measures ANOVAs assessed differences between groups and the 4 visual conditions. Alpha level was set at $p=0.05$.

A condition main effect for both TTB-ML ($F_{3,138}=22.9$; $p<0.001$) and TTB-AP ($F_{3,138}=93.7$; $p<0.001$) was observed. Specifically, our observed main effects were driven by differences between the eyes-open condition and the eyes-closed condition

for TTB ML ($p=0.006$) and TTB AP ($p<0.001$). Additionally, significant differences in TTB-AP were found between eyes-open and both low- ($p<0.001$) and high-occlusion ($p<0.001$).

Those with and without CAI have impaired postural control under limited and no vision conditions. Both occlusion conditions produced similar postural control outcomes as eyes-closed, suggesting a disruption to the sensorimotor system. Future research should examine the effect of stroboscopic eyewear on postural control in single-limb support and functional activities as well as the effect of stroboscopic eyewear as a functional rehabilitation tool for those with CAI.

Introduction

Chronic ankle instability (CAI) is a debilitating condition of the ankle joint characterized by recurrent sprains, episodes of “giving way”, pain, or weakness in the ankle.^{1,2,4} CAI arises from an acute sprain of the ankle, one of the most commonly occurring injuries seen in active populations.^{17,18} It has been estimated that 40% of individuals who sustain an ankle sprain develop CAI which decreases in physical activity and facilitates post-traumatic ankle osteoarthritis development.⁴⁻⁶

Individuals with CAI have sensorimotor adaptations that are a result of the initial ligamentous injury and lead to postural control deficits.⁹ These adaptations include altered somatosensory input and neuromuscular responses that leave the individual vulnerable to re-injury.^{25,26,29} A cascade of events is thought to follow damaged mechanoreceptors upon initial injury leading to long-lasting alterations in cortical level somatosensory integration and resultant reliance on visual information to maintain postural control.⁹⁻¹¹

First, initial ligamentous injury interrupts once continuous somatosensory input from the joint to higher level integration centers regarding joint position, stress, and velocity.^{9,11} Without this information, the central nervous system must adopt a new strategy of obtaining sufficient information for dictation of motor strategies to maintain postural control.^{9,11} It appears that in the absence of sufficient somatosensory input, the motor control system reweights the level of visual feedback used to prepare for and respond to external perturbation.⁹ Over time, the motor control system begins to rely on visual feedback to produce appropriate motor responses^{9,11} and long-term changes to the somatosensory system are seen.^{25,26,29} A recent meta-analysis found that

individuals with CAI have significantly worse postural control measures during single-limb balance tasks under eyes-closed conditions compared to eyes-open.¹² While it is true that healthy controls also have worse postural control under eyes-closed conditions compared to eyes-open, the magnitude of change from eyes-open to eyes-closed conditions are greater in the CAI population.^{12,43} This indicates that those with CAI lack appropriate sensorimotor compensation when visual information is disturbed and, therefore, suggests a reliance on visual information to maintain postural control.¹² It is unclear whether long-term visual reliance in CAI patients is a positive or negative adaptation.

Whether or not a reliance on visual information is a positive or negative adaptation, the topic is worth exploring in future research. Current balance training methods often involve exercises in static posture with eyes closed^{13,14} that do not alter visual reliance in CAI.¹⁵ Incorporating dynamic postural exercises with limited visual information to stress the sensory reweighting mechanism should be explored as a method of examining visual reliance. Research has shown that interrupting visual information with stroboscopic eyewear caused significant postural instability during single-limb stance (SLS) compared to eyes open conditions in healthy subjects.¹⁶ Current literature surrounding the postural response of the CAI population to interrupted visual information is non-existent. Therefore, the purpose of this study was to examine changes in spatiotemporal measures of postural control during balance conditions with varying levels of visual occlusion in those with CAI and healthy controls. We hypothesized that worse spatiotemporal postural control outcomes (i.e. shorter time-to-boundary) would be exhibited in those with and without CAI during

balance conditions with any limitation in visual information compared to eyes open. Furthermore, we hypothesize that those with CAI would have significantly worse postural control outcomes compared to healthy controls during limited vision conditions.

Methods

Study Design

This quasi-experimental cross-sectional study was approved by the university's institutional review board and performed in a clinical research center. Participants completed a postural control assessment in double-limb support under varying levels of visual input as the final assessment within the larger study's assessment battery that included various visual and balance performance measures.

Participants

Fifty-one participants (15 males (29.4%); age=21.1(2.0 years; mass=66.2 (10.7 kg; height=1.7(0.1 m)) participating in a larger study were included in the present investigation. Participants who met the International Ankle Consortium inclusion criteria recommendations² (n=35) were included in the CAI group while healthy participants (n=16) had no history of lower extremity injury. All participants were physically active, defined as participating in moderate to vigorous activity at least 3 days per week for at least 30 minutes, over the past 3 months. All participants provided written informed consent prior to study participation. **Table 1** outlines participant demographic information.

Instrumentation

A triaxial forceplate (AMTI, Watertown, MA) was used to examine postural

control by recording center-of-pressure (COP) measurements at a sampling frequency of 100Hz via Balance Clinic software (version 2.02.01). A Matlab software program (MathWorks, Inc., Natick, MA, USA) was used to compute the postural control outcomes. Low (level 2) and high (level 6) visual occlusion conditions were produced using Senaptec Strobe Training Goggles (Senaptec, Beaverton, OR).

Procedures

The postural control balance protocol required participants to complete a 3-minute trial in double-limb support (DLS) under four visual conditions: 1) eyes-open, 2) low-occlusion, 3) high-occlusion, and 4) eyes-closed. Participants were instructed to stand as still as possible with arms at side and focus on a self-selected point on the wall in front of them. Placement of the feet was marked to capture foot width and length and ensure consistency between all trials.^{69,70}

Outcomes

Time-to-boundary minima means in the anteroposterior (TTB-AP) and mediolateral (TTB-ML) directions were calculated in seconds, as previously described by Hertel et al.⁷⁰ TTB uses COP excursion velocity and position in reference to the boundaries of the base-of-support to estimate the time a person has to make a postural correction before the COP reaches a base-of-support boundary assuming that COP excursion direction and velocity remain constant⁷⁰. A shorter TTB indicates worse postural control.⁷¹ Time-to-boundary minima mean has been shown to be a reliable measure of postural control (ICC=0.62-0.87).⁷⁰ In addition, this measure has been found to be more sensitive to postural control differences between those with CAI and healthy controls compared to other COP measures that do not consider base of support.^{69,72}

Original forceplate COP data were processed with a fourth order, zero-lag, low-pass Butterworth filter with a cutoff frequency of 5 Hz.^{43,69,72} Data from the 1st minute of each trial acted as four 15-second trials to allow better congruence with previous methodology in this space.^{12,44} Due to a limited sample size, TTB AP and TTB ML outliers—defined as falling above or below 2 standard deviations of the mean—were adjusted by averaging the preceding two extreme values.

Statistical Analysis

Separate two-way repeated measures ANOVAs were used to assess differences between groups (CAI vs. healthy) and visual conditions (eyes-open, low-occlusion, high-occlusion, and eyes-closed) on TTB AP/ML minima means using statistical software (SAS 94). Hedge's *g* effect sizes and 95% confidence intervals were calculated between conditions. A-priori alpha level was set to $p=0.05$.

Results

All subjects completed the full 3-minute trial under each visual condition, with the exception of one who felt dizzy under the first stroboscopic condition, discontinued the testing session, and was removed from the study. We did not observe any Group x Condition interaction for TTB-AP ($F_{3,196}=0.55$; $p=0.652$) or TTB-ML ($F_{3,196}=0.35$; $p=0.788$). No group main effects were observed for TTB-AP ($F_{1,46}=1.57$; $p=0.211$) or TTB-ML ($F_{1,46}=0.10$; $p=0.757$). We did observe a condition main effect for both TTB-AP ($F_{3,138}=93.7$; $p<0.001$) and TTB-ML ($F_{3,138}=22.9$; $p<0.001$). Specifically, our observed main effects were driven by differences between the eyes-open condition and the eyes-closed condition for TTB AP ($p<0.001$) TTB ML ($p=0.006$). Additionally, significant differences in TTB-AP were found between eyes-open and both low- ($p<0.001$) and

high-occlusion ($p < 0.001$). No significant difference was found between eyes-closed and low- or high-occlusion conditions. **Tables 2 & 3** present all data related to these analyses.

Discussion

Both CAI and healthy groups had significantly worse postural control (TTB AP) under conditions of limited vision compared to eyes open. These results provide implications for future research in the use of stroboscopic eyewear clinically as a rehabilitation tool. Our results refuted our hypothesis, showing no significant difference in the postural control response to progressive visual occlusion between CAI and healthy participants in DLS. These findings suggest that potentially a more complex balance task is needed to identify differences in postural control response to limited visual conditions between those with CAI and healthy controls.

Those with CAI do not respond differently than healthy controls to progressively limited visual conditions during a DLS assessment. To the best of our knowledge, the response of those with CAI to stroboscopic conditions has not been previously examined, however it has been investigated in the healthy population. Kim et al. found that postural control under stroboscopic conditions was worse compared to eyes-open and better compared to eyes-closed conditions in healthy participants standing in single-limb support (SLS).⁷³

We suspected those with CAI to respond differently based on meta-analysis by Song et al. that revealed a greater balance disruption with complete removal of visual information in CAI participants compared to controls in SLS, suggesting a reduced ability of the sensorimotor system to compensate for the removal of visual input by

reweighting use of other sensory systems.¹⁵ Healthy individuals rely more heavily on visual information with increasingly complex postural control tasks, but are able to compensate by reweighting the use of other, more available sensory systems to maintain postural stability.⁷⁴ Those who cannot compensate in this way would, therefore, be susceptible to greater postural control deficits during complex tasks when visual information is removed. We reasoned that the reduced ability of CAI participants to reweight would be demonstrated under conditions of partially occluded vision, however this was not the case. This could be due to insufficient challenge of the sensorimotor system, as the present study was completed in DLS, a low-complexity balance task.⁷⁴ Without a complex task, such as single-limb balance, visual reliance and resultant postural control deficits in CAI may not be perceivable.

Postural control results between limited visual conditions may have been influenced by practice effect. Trial durations in the present study were longer than is typical to collect postural control data (3 minutes vs 10-30 seconds)^{12,44}, and sequence of visual conditions was not randomized. There is evidence that human stance stability improves with the repetition of the task.⁷⁵ This could mean that postural control deficits observed in limited-vision trials performed after an eyes-open trial are underestimated. Further research should explore postural control response in the CAI population in SLS with shorter, randomized trials under various visual conditions.

The primary finding of this study was that regardless of group, individuals had worse postural control under conditions with any visual occlusion compared to eyes-open. Additionally, postural control was similar between the stroboscopic conditions and the eyes-closed condition. This may have significant rehabilitative implications.

Current balance training programs for those with CAI improve postural control but fail to alter sensory reweighting abilities.¹⁵ These training programs provide limited opportunities to target visual reliance and instead rely on eyes-open stance on a single limb and/or unstable surface. Both SLS and unstable surfaces have been shown to increase an individual's reliance on visual information.¹⁵ While static balance tasks under eyes-closed conditions would address this problem early in rehabilitative programs, such exercises may not challenge the sensorimotor system enough to provoke lasting retraining/reorganization of this system particularly in dynamic real-world scenarios. Because stroboscopic conditions are as effective in stressing the sensory reweighting mechanism as an eyes-closed condition, indicated by our results, this tool could be used to tax the sensorimotor system while completing more complex, dynamic exercises in those with CAI to promote better sensory reweighting abilities.

A better understanding of the capacity to train sensory reweighting may help determine whether visual reliance is a beneficial or detrimental adaptation. If recovery of normal somatosensory system function is not possible (evidenced by failure of balance training to improve postural control under eyes-closed conditions¹⁵) then reliance on visual information may be a necessary adaptation to maintain postural control and avoid injury.¹¹ However, if sensory information from mechanoreceptors is accurately perceived and interpreted, and it is possible to reintegrate this information through enhancing sensory reweighting abilities, then visual reliance would be considered a negative adaptation, as inability to integrate somatosensory information may increase risk of injury when visual information is absent or in high demand (such as in sport).

Stroboscopic vision could be useful in studying sensory reweighting capabilities. It is unclear if stroboscopic vision encourages the upregulation of other sensory systems or trains the visual processing system to function more efficiently with less visual information. Further research in this area is necessary to define the effect of stroboscopic vision on sensory integration strategies and explore the use of stroboscopic vision training in rehabilitation of visual reliance in CAI.

Conclusions

Those with and without CAI have worse postural control under conditions of partially or fully occluded vision. Low-occlusion and high-occlusion conditions produced similar postural control outcomes as the eyes-closed condition, indicating a similar disruption to the sensorimotor system. Future research on implementing stroboscopic eyewear in functional rehabilitation for those with CAI is warranted.

Conflict of Interest Statement

Dr. Jason Mihalik, a co-investigator on this study, holds some ownership interest in Senaptec LLC, the company that sells the Senaptec Strobe eyewear which were used to collect data for this study. A committee at UNC-Chapel Hill has reviewed the relationships and concluded any possible benefit to the investigators was not likely to affect participant safety or the scientific quality of the study.

CHAPTER V

Overview

Individuals with chronic ankle instability (CAI) have postural control deficits due to sensorimotor system adaptations. Sensory reweighting dysfunction, specifically a reliance on visual information, is seen in this population, however it is not well understood. The purpose of this study is to test the influence of sensory integration, visual function, and visual performance measures on postural control under varying levels of visual occlusion.

Thirty-five participants (9 males (25.7%); age=21.1±1.9 years; mass=65.9±10.3 kg; height=1.7±0.9 m) with self-reported CAI completed a two hour testing session. Independent variables included scores on the Sensory Organization Test and Senaptec Sensory Station battery of visual function and performance assessments. Dependent variables included time-to-boundary (TTB) in the anteroposterior and mediolateral directions during bipedal stance under four visual conditions (eyes-open, low-occlusion, high-occlusion, and eyes-closed).

Stepwise regression models were evaluated for eyes-open and limited-vision conditions. Select visual performance variables included in the eyes-open model significantly explained 18% of the variance in TTB AP ($R^2=0.18$, $p=0.013$) and 39% of the variance in TTB ML ($R^2=0.39$, $p<0.001$). Specifically, better perception span

($R^2=0.26$, $p=0.002$) significantly predicted increased, or better, TTB ML and worse target capture ($R^2=0.13$, $p=0.016$) significantly predicted decreased, or worse, TTB ML. Better perception span ($R^2=0.18$, $p=0.013$) significantly predicted increased TTB AP in the eyes-open model. In the limited-vision model, perception span significantly explained 17% and 18% of the variance in TTB AP ($R^2=0.17$, $p=0.016$) and TTB ML ($R^2=0.18$, $p=0.015$) respectively.

Better performance on certain visual performance measures may predict better postural control under varying levels of visual occlusion. Future research should explore the influence of other sensory function and integration measures on postural control in CAI, as well as examine this population prospectively to help explain the development of visual reliance.

Introduction

Postural control in the healthy human is accomplished via the sensorimotor system which centrally integrates sensory information from visual, vestibular, and somatosensory receptors to formulate motor responses that create dynamic joint stability.²² Dysfunction in any component of the sensorimotor system is thought to increase risk of injury as the individual is less effective in preparing for and responding to varying environmental conditions. Sensorimotor system adaptations with resulting postural control deficits have been consistently found in individuals with chronic ankle instability (CAI).^{43,72,76} Most recently, those with CAI were observed to have an increased reliance on visual information.^{12,23} Increased reliance on visual information is believed results from a cascade of events initiated with damage to somatosensory receptors in the tendinous and capsuloligamentous structures of the ankle upon initial injury (i.e. deafferentation).⁹⁻¹¹

In a healthy sensorimotor system, it is generally accepted that the integration of sensory information is weighted depending on reliability and availability of each sensory system.²³ The up- and down-regulation of sensory information (i.e. sensory reweighting) is dynamic and vital for creating the perception of one's environment.^{23,77} With limited proprioceptive feedback from the ankle joint after injury (i.e. deafferentation), the sensorimotor system must adopt a new strategy in order to obtain sufficient sensory information to guide motor response and maintain postural control.^{9,11} It appears that with insufficient somatosensory input, the motor control system of those with CAI downregulates use of this system and upregulates reliance on visual feedback to maintain postural control.^{11,78}

The mechanism of prolonged visual reliance is not well understood. It remains unclear what factors may influence the development of this adaptation. Sensory integration dysfunction is assumed to contribute to visual reliance, however there is little evidence directly relating sensory integration to postural control under varying visual conditions. The Sensory Organization Test (SOT) assesses one's ability to maintain postural control when each sensory system is required to compensate for alteration or absence of other systems, theoretically indicating sensory integration abilities.⁷⁹ This measure could help assess the role of sensory integration in postural control under varying levels of visual occlusion in those with CAI. Likewise, despite the emphasis placed on the visual system in those with CAI, there is currently little information regarding visual function and performance in this population and how these abilities may relate to postural control under varying levels of visual occlusion. The Senaptec Sensory Station is a recently developed, interactive computerized system which assesses many aspects of visual function and performance.⁸⁰ Exploring the influence of sensory integration, visual function, and visual performance on postural control in those with CAI may help guide the discussion of visual reliance in this population.

Therefore, the purpose of this study is to test the influence of sensory integration, visual system function, and visual system performance on postural control under varying levels of visual occlusion in those with CAI. We predict that shorter (worse) time-to-boundary under limited-vision conditions will be associated with a lower somatosensory ratio score and a higher visual ratio score of the Sensory Organization Test. Further, we hypothesize that shorter time-to-boundary under

limited-vision conditions will be associated with poor visual performance scores, specifically those utilizing peripheral visual field information, as visual processing in the peripheral field is believed to contribute largely to postural control.⁸¹

Methods

Study Design

Participants completed one 2-hour long testing session. The first portion of the testing session involved a series of brief oculomotor and visual function assessments that were used as part of the larger study. Visual function and performance were then assessed using the Senaptec Sensory Station battery. Sensory integration was assessed using the Sensory Organization Test. Finally, an assessment of postural control was completed involving double-limb balance on a triaxial forceplate under varying levels of visual input.

Participants

This study's procedures were approved by the university's Institutional Review Board. Thirty-five participants (9 males (25.7%); age=21.1±1.9 years; mass=65.9±10.3 kg; height=1.7±0.9 m) participating in a larger study were included in the present investigation. All participants qualified as having CAI according to the International Ankle Consortium inclusion criteria recommendations² and were physically active. Physically active was defined as completing moderate to vigorous activity at least 3 times per week for at least 30 minutes during the past 3 months. Recruitment of participants within the university population was accomplished by email or in person. **Table 1** outlines participant demographic information.

Visual Performance

The Senaptec Sensory Station (Senaptec, Beaverton, Oregon) was used to assess visual function and performance. The system consists of two touch-sensitive, high resolution liquid crystal monitors (22-inch and 42-inch) controlled by a single computer and a Motorola Moto G3 smartphone (Motorola Mobility, LLC, Schaumburg, IL) used remotely to register participant responses to the Senaptec system assessments. The Senaptec Sensory Station assessment takes approximately 25 minutes to complete and includes a battery of 10 tests: visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple object tracking, hand-reaction time, target capture, hand-eye-coordination, and go-no-go. Participants were provided verbal instruction on, a demonstration of, and allowed to practice prior to completing each test. **Table 4** provides a detailed explanation for each test and describes the outcomes of interest that served as our independent variables. The Senaptec Sensory Station is the successor to a comparable computer-based system (Nike Sensory Station)⁸⁰ of which these series of visual function and performance tests have been found reliable.⁶⁷

Sensory Integration

Sensory integration was evaluated using the Sensory Organization Test (SOT) of the SMART Balance Master (NeuroCom International, Clackamas, OR). The SOT measures dynamic posturography using two 9 X 18 inch force plates under 6 conditions designed to alter the visual, vestibular, and visual sensory systems: 1) eyes open, stationary support surface, 2) eyes closed, stationary support surface, 3) eyes open, sway-referenced visual input with stationary support surface, 4) eyes open with sway-referenced support surface, 5) eyes closed with sway-referenced support surface, and

6) eyes open, with sway-referenced visual and support surface. Each condition is repeated 3 times for a total of eighteen, 20 second trials. Participants stood without shoes on the system's forceplates in double-limb support. Foot placement was adjusted per system requirements, and was readjusted if movement during the trial occurred. Participants were instructed to stand as still as possible with their arms at their sides and remain quiet throughout the trials. The first 6 trials were completed in order of conditions 1-6 to acclimate the participant to the test. The next 6 trials began with condition 1, followed by condition 2, followed by conditions 3-6 in an operator-randomized order. The last 6 trials were randomized by the operator. SOT procedures have been thoroughly detailed in previous work.⁶⁸

Equilibrium scores for each trial were computed based on an algorithm developed for the SMART Balance Master and used to calculate an overall composite score and three ratio scores (vestibular, visual, and somatosensory) for each participant. The composite score represents the weighted average sway across all testing conditions. Better postural control is indicated by a higher composite score.⁶⁸ The ratio scores represent the individual's ability to use the specified sensory system to maintain balance when the other two systems are unavailable or altered⁶⁸. Vestibular, visual, and somatosensory ratio scores are calculated by comparing select conditions (5, 4, and 2 respectively) to the reference condition (1) in which all sensory systems are available and unaltered. Higher ratio scores represent better ability to integrate information for the specific sensory system.⁶⁸

Postural Control

A triaxial forceplate (AMTI, Watertown, MA) was used to examine postural

control by recording center-of-pressure (COP) measurements at a sampling frequency of 100Hz via Balance Clinic software (version 2.02.01). A Matlab software program (MathWorks, Inc., Natick, MA, USA) was used to compute the postural control outcomes. Low (level 2) and high (level 6) visual occlusion conditions were produced using stroboscopic eyewear (Senaptec, Beaverton, Oregon). Participants completed a 3-minute trial in double-limb support under four visual conditions: 1) eyes-open, 2) low-occlusion, 3) high-occlusion, and 4) eyes-closed. Participants were instructed to stand still with arms at side and focus on a self-selected point on the wall in front of them. Foot placement was preserved between trials to ensure consistency.

Time-to-boundary minima means in the anteroposterior (TTB-AP) and mediolateral (TTB-ML) directions served as dependent variables in this study. Previously described by Hertel et al,⁷⁰ TTB ML and TTB AP are calculated in seconds using COP excursion velocity and position as well as the dimensions of the individual's base-of-support. TTB is an estimate of the time a person has before their COP would extend past the base of support, resulting in balance loss, if a postural correction is not made.⁷⁰ Therefore, a shorter TTB indicate worse postural control.⁷¹ TTB has been shown to be reliable (ICC=0.62-0.87).⁷⁰ This measure is commonly used because it has greater sensitivity to postural control differences between the CAI population and healthy controls compared to other COP measures.^{69,72} Raw COP data were processed with a fourth order, zero-lag, low-pass Butterworth filter with a cutoff frequency of 5 Hz.^{69,72} Due to a limited sample size, outliers—defined as falling outside 2 standard deviations above or below the mean—were adjusted by averaging the preceding two extreme values. Our previous work showed no significant difference between low-

occlusion, high-occlusion, and eyes-closed conditions for either TTB AP or TTB ML outcomes for the CAI group.¹⁹ Therefore, TTB AP and TTB ML minima means for each participant were averaged across the 3 conditions and this average was used in further analysis to represent a “limited” condition.

Statistical Analysis

To test the influence of individual sensory system integration ability on postural control under eyes-open and limited-visual conditions in those with CAI, four multivariable regressions were calculated (two conditions, two dependent variables). Visual, vestibular, and somatosensory ratio scores were put into the models consistently in that order.

To test the influence of visual function and performance on postural control under eyes-open and limited-visual conditions, first univariable regressions were computed to evaluate individual relationships between the 10 Senaptec subtest's and postural control outcomes (TTB AP/ML) under the eyes-open and limited conditions. Univariable relationships that demonstrated a p-value of $p \leq 0.1$ were considered for inclusion in the stepwise models. Two stepwise multivariable regressions (eyes-open and limited conditions) were evaluated to examine the influence of visual system performance measures on postural control outcomes under varying levels of visual occlusion in those with CAI. Sequence of input into the greater models was determined based on the Senaptec variables that demonstrated the greatest relationship with each dependent variable separately. A-priori alpha level was set to $p=0.05$.

Results

Senaptec data for two participants was lost due to network error. Descriptive statistics for independent variables can be found in **Table 5**. There were no significant interactions between the SOT variables in either the eyes-open or limited-vision model. Sensory Organization Test variables had no significant relationship with TTB AP or TTB ML in the eyes-open ($R^2=0.06$, $F_{1,34}=0.69$, $p=0.57$; $R^2=0.13$, $F_{1,34}=1.56$, $p=0.22$) or the limited-vision ($R^2=0.09$, $F_{1,34}=1.05$, $p=0.38$; $R^2=0.10$, $F_{1,34}=1.12$, $p=0.36$) regression model.

Results of simple linear regressions where Senaptec scores with a bivariate correlation of $r > 0.2$ or $r < -0.2$ with either dependent variable were identified for inclusion in respective multiple regression models (**Tables 6 & 7**). Senaptec stepwise regression models for eyes-open and limited visual conditions can be found in **Tables 8 & 9**. Senaptec predictor variables included in the eyes-open model significantly explained 39% of the variance in TTB ML ($R^2=0.39$, $F_{1,32}= 9.72$, $p<0.001$) and 18% of the variance in TTB AP ($R^2=0.18$, $F_{1,32}= 6.9$, $p=0.013$). Specifically, better perception span ($R^2=0.26$, $\beta= 0.76$, $p=0.002$) significantly predicted increased, or better, TTB ML and worse target capture ($R^2=0.13$, $\beta=-0.10$, $p=0.016$) significantly predicted decreased, or worse, TTB ML. Additionally, better perception span ($R^2=0.18$, $\beta=0.23$, $p=0.013$) significantly predicted increased TTB AP in the eyes-open model. In the limited-vision model, perception span significantly explained 17% and 18% of the variance in TTB AP ($R^2=0.17$, $F_{1,32}= 6.5$, $\beta=0.23$, $p=0.016$) and TTB ML ($R^2=0.18$, $F_{1,32}= 6.7$, $\beta=0.63$, $p=0.015$) outcomes, respectively.

Discussion

The main finding of this study was that some visual performance measures predict postural control outcomes in those with CAI in both eyes-open and limited-vision conditions. Results of this study did not find a significant relationship between the ability to use different sensory systems, as measured by SOT ratio scores, and postural control under eyes-open or limited-vision conditions.

The ratio scores of the SOT are theoretically a measure of one's ability to utilize sensory information (visual, vestibular, and somatosensory) by selectively isolating each system. It is possible that there is no relationship between individual sensory integration ability and postural control in those with CAI, however this conclusion seems unlikely given reported sensorimotor adaptations and related postural control deficits in this population.²⁰ It is more plausible that a larger sample size or a more comprehensive assessment of sensorimotor system ability including sensory system function and integration is needed to examine this relationship. If one is unable to accurately receive sensory information, processing of that information may also be inaccurate, resulting in improper postural response. Semmes Weinstein Monofilaments,²⁷ vibratory threshold, and joint position replication³⁶ have all been used to measure somatosensory function. Several measures of visual function are commonly used, such as the Snellen Eye Chart which measures sharpness of vision,⁸² or the Pelli-Robson Chart which measures contrast sensitivity.⁸³ Vestibular system function has been measured with various assessments including the Subjective Visual Vertical exam.⁸⁴ Examining proficiency of individual sensory system receptors along with sensory integration ability may provide a more comprehensive assessment of

sensorimotor system function. Additionally, sensory integration dysfunction in CAI may not have been provoked in double-limb support, a low-complexity balance task⁷⁴ implemented in the current study. Several previous studies have found postural control deficits in those with CAI in single-limb support.^{43,69,72} More complex balance tasks, such as single-limb support, may be necessary to stress the sensorimotor system enough to observe dysfunction.

Our hypothesis was partially correct that better visual performance, specifically on perception span and target capture subtests, predicted better postural control outcomes under the eyes-open and limited-vision conditions. Perception span uses spatial memory to identify the location of a stimulus after it disappears.⁸⁵ This test relates to postural control as improved ability to recall the orientation of one's surroundings is beneficial in maintaining postural control. In those who rely on visual information (CAI), this skill would be important in maintaining postural control, especially under conditions that partially or completely disrupt visual information. In addition to Perception Span, Target Capture performance, while only significantly related to one postural control outcome (TTB ML) under the eyes-open condition, may have broader implications for future research. The Target Capture subtest assesses one's ability to quickly recognize a stimulus that requires attention and respond to it correctly.⁸⁵ To maintain postural control, it is crucial that one can determine conditions within the immediate environment that may pose a threat to stability and respond correctly.

Performance of other aspects of the visual system may be related to postural control in CAI that were not observed in the present study. More sensitive measures of

visual performance or a more complex balance task could be used to further explore this relationship.

Furthermore, prospective investigations are needed to assess visual reliance and underlying mechanisms at different time points (pre-injury, immediately following injury) as reliance on visual information is thought to develop over time due to chronically compensating for dysfunction in the somatosensory system upon initial injury.^{11,76}

Additional limitations of this study include small sample size of only recreationally active participants. The current study also did not account for number of ankle sprains or amount of medical care sought and received. These factors could influence the relationships examined in this study.

Conclusion

Those with CAI who performed better on the Senaptec Sensory Station's Perception Span and Target Capture also showed better postural control under eyes-open (PS and TC) and limited-vision conditions (PS only). Sensory integration ability, as measured by SOT, and postural control under eyes-open or limited-vision conditions were not related. Future research should explore the influence of sensory integration and visual performance measures on more complex postural control tasks in CAI, as well as examine this population prospectively to help explain the development of visual reliance

REFERENCES

1. Yeung MS, Chan KM, So CH, Yuan WY. An epidemiological survey on ankle sprain. *Br J Sp Med*. 1994;28(2).
<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1332043/pdf/brjmed00014-0042.pdf>. Accessed September 30, 2017.
2. Gribble PA, Delahunt E, Bleakley CM, et al. Selection Criteria for Patients With Chronic Ankle Instability in Controlled Research: A Position Statement of the International Ankle Consortium. *J Athl Train*. 2014;49(1):121-127.
doi:10.4085/1062-6050-49.1.14
3. Kannus P, Renstrom P. Current Treatment of the Lateral Concepts for Acute Ligaments Tears of the Ankle. *J Bone Jt Surg*. 1991;73(2):305-312.
4. Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Recovery From a First-Time Lateral Ankle Sprain and the Predictors of Chronic Ankle Instability A Prospective Cohort Analysis. *Am J Sports Med*. 2016;44(4):995-1003.
doi:10.1177/0363546516628870
5. Hintermann B, Boss A, Schä D. Arthroscopic Findings in Patients with Chronic Ankle Instability. *Am J Sports Med*. 2002;30(3):402-409.
<http://journals.sagepub.com/doi/pdf/10.1177/03635465020300031601>.
Accessed October 1, 2017.
6. Harrington KD. Degenerative arthritis of the ankle secondary to long-standing lateral ligament instability. *J Bone Joint Surg Am*. 1979;61(3):354-361.
<http://www.ncbi.nlm.nih.gov/pubmed/429402>.
7. Hubbard-Turner T, Turner MJ. Physical Activity Levels in College Students With Chronic Ankle Instability. *J Athl Train*. 2015;50(7):742-747. doi:10.4085/1062-6050-50.3.05
8. Gribble PA, Bleakley CM, Caulfield BM, et al. Evidence review for the 2016 International Ankle Consortium consensus statement on the prevalence, impact and long-term consequences of lateral ankle sprains. *Br J Sports Med*. 2016;50(24):1496-1505. doi:10.1136/bjsports-2016-096189

9. Needle AR, Lepley AS, Grooms DR. Central Nervous System Adaptation After Ligamentous Injury: a Summary of Theories, Evidence, and Clinical Interpretation. *Sport Med.* 2017;47(7):1271-1288. doi:10.1007/s40279-016-0666-y
10. Brown CN, Ross SE, Mynark R, Guskiewicz KM. Assessing Functional Ankle Instability with Joint Position Sense, Time to Stabilization, and Electromyography.pdf. *J Sport Rehabil.* 2004;13:122-134.
11. Grooms D, Appelbaum G, Onate J. Neuroplasticity Following Anterior Cruciate Ligament Injury: A Framework for Visual-Motor Training Approaches in Rehabilitation. *J Orthop Sport Phys Ther.* 2015;45(5):381-393. doi:10.2519/jospt.2015.5549
12. Song K, Burcal CJ, Hertel J, Wikstrom EA. Increased Visual Use in Chronic Ankle Instability: A Meta-analysis. *Med Sci Sports Exerc.* 2016;48(10):2046-2056. doi:10.1249/MSS.0000000000000992
13. Smith RW, Reischl SF. Treatment of ankle sprains in young athletes. *Am J Sports Med.* 1986;14(6):465-471. <http://journals.sagepub.com/doi/pdf/10.1177/036354658601400606>. Accessed October 7, 2017.
14. Ashton-Miller JA, Wojtys EM, Huston LJ, Fry-Welch D. Can proprioception really be improved by exercises? *Knee Surgery, Sport Traumatol Arthrosc.* 2001;9(3):128-136. doi:10.1007/s001670100208
15. Song K, Rhodes E, Wikstrom EA. Balance Training Does Not Alter Reliance on Visual Information during Static Stance in Those with Chronic Ankle Instability: A Systematic Review with Meta-Analysis. *Sport Med.* 2017:1-13. doi:10.1007/s40279-017-0850-8
16. Kim K-M, Kim J-S, Grooms DR. Article Title: Stroboscopic Vision to Induce Sensory Reweighting During Postural Control. *Grooms DR J Sport Rehabil.* 2017. doi:10.1123/jsr.2017-0035
17. Hootman JM, Dick R, Agel J. Epidemiology of Collegiate Injuries for 15 Sports: Summary and Recommendations for Injury Prevention Initiatives. *J Athl Train.*

2007;31142(2):311-319. www.journalofathletictraining.org. Accessed September 30, 2017.

18. Shah, S., Thomas, A.C., Noone, J.M., Blanchette, C.M., Wikstrom EA. Incidence and Cost of Ankle Sprains in United States Emergency Departments. *Sage Journals*. 2016;8(6):547-552.
19. Taga I, Shino K, Inoue M, Nakata K, Maeda A. Articular cartilage lesions in ankles with lateral ligament injury An arthroscopic study*. *Am J Sports Med*. 1993;21(1):120-127.
<http://journals.sagepub.com.libproxy.lib.unc.edu/doi/pdf/10.1177/036354659302100120>. Accessed November 25, 2017.
20. Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *J Athl Train*. 2002;36437(44):364-375.
www.journalofathletictraining.org. Accessed October 1, 2017.
21. Hertel J. Functional Instability Following Lateral Ankle Sprain. *Sport Med*. 200AD;29(5):361-371.
<https://link.springer.com/content/pdf/10.2165%2F00007256-200029050-00005.pdf>. Accessed October 7, 2017.
22. Riemann BL, Lephart SM. The Sensorimotor System, Part I: The Physiologic Basis of Functional Joint Stability. *J Athl Train*. 2002;37(1):71-79.
www.journalofathletictraining.org. Accessed April 2, 2018.
23. Peterka RJ. Sensorimotor Integration in Human Postural Control. *J Neurophysiol*. 2002;88:1097-1118.
24. Terada M, Bowker S, Thomas AC, Pietrosimone B, Hiller CE, Gribble PA. Corticospinal Excitability and Inhibition of the Soleus in Individuals With Chronic Ankle Instability. *Am Acad Phys Med Rehabil*. 2016;8:1090-1096.
doi:10.1016/j.pmrj.2016.04.006
25. Hoch MC, McKeon PO, Andreatta RD. Plantar vibrotactile detection deficits in adults with chronic ankle instability. *Med Sci Sports Exerc*. 2012;44(4):666-672.
doi:10.1249/MSS.0b013e3182390212

26. Hertel J. Sensorimotor Deficits with Ankle Sprains and Chronic Ankle Instability. *Clin J Sport Med*. 2008;27:353-370. doi:10.1016/j.csm.2008.03.006
27. Powell MR, Powden CJ, Houston MN, Hoch MC. Plantar cutaneous sensitivity and balance in individuals with and without chronic ankle instability. *Clin J Sport Med*. 2014;24(6):490-496. doi:10.1097/JSM.0000000000000074
28. Kim KM, Hart JM, Saliba SA, Hertel J. Modulation of the fibularis longus hoffmann reflex and postural instability associated with chronic ankle instability. *J Athl Train*. 2016;51(8):637-643. doi:10.4085/1062-6050-51.10.05
29. Kim K-M, Ingersoll CD, Hertel J. Altered postural modulation of Hoffmann reflex in the soleus and fibularis longus associated with chronic ankle instability. *J Electromyogr Kinesiol*. 2012;22:997-1002. doi:10.1016/j.jelekin.2012.06.002
30. Song K, Kang TK, Wikstrom EA, Jun H pil, Lee SY. Effects of reduced plantar cutaneous sensation on static postural control in individuals with and without chronic ankle instability. *J Sci Med Sport*. 2017;20(10):910-914. doi:10.1016/j.jsams.2016.04.011
31. Arnold BL, Docherty CL. Low-load eversion force sense, self-reported ankle instability, and frequency of giving way. *J Athl Train*. 2006;41(3):233-238.
32. Boyle J, Negus V. Joint position sense ill the recurrently sprained ankle. *Aust J Physiother*. 1998;44:159-163. doi:10.1016/S0004-9514(14)60375-5
33. Glencross D, Thornton E. Position sense following joint injury. *J Sports Med Phys Fitness*. 1981;21(1):23-27. <http://www.ncbi.nlm.nih.gov/pubmed/7278217>. Accessed April 9, 2018.
34. Burcal CJ, Wikstrom EA. Plantar Cutaneous Sensitivity With and Without Cognitive Loading in People With Chronic Ankle Instability, Copers, and Uninjured Controls. *J Orthop Sport Phys Ther*. 2016;46(4):270-276. doi:10.2519/jospt.2016.6351
35. Ushio M, Murofushi T, Chihara Y, Iwasaki S, Yamaguchi T, Kaga K. Testing of vibratory thresholds as a clinical examination for patients with unsteadiness due to somatosensory disorders. *Gait Posture*. 2008;28:552-558. doi:10.1016/j.gaitpost.2008.03.010

36. Switlick T, Kernozek TW, Meardon S. Differences in Joint-Position Sense and Vibratory Threshold in Runners with and Without a History of Overuse Injury. *J Sport Rehabil.* 2015;24(1):6-12. doi:10.1123/jsr.2013-0089
37. Mcvey ED, Palmieri RM, Docherty CL, Zinder SM, Ingersoll CD. Arthrogenic Muscle Inhibition in the Leg Muscles of Subjects Exhibiting Functional Ankle Instability. *Foot Ankle Int.* 2005;26(12):1055-1061.
<http://journals.sagepub.com.libproxy.lib.unc.edu/doi/pdf/10.1177/107110070502601210>. Accessed March 26, 2018.
38. Palmieri RM, Ingersoll CD, Hoffman MA. The Hoffmann Reflex : Methodologic. *J Athl Train.* 2004;39(3):268-277.
39. Bowker S, Terada M, Thomas AC, Pietrosimone BG, Hiller CE, Gribble PA. Neural Excitability and Joint Laxity in Chronic Ankle Instability, Coper, and Control Groups. *J Athl Train.* 2016;51(4):336-343. doi:10.4085/1062-6050-51.5.05
40. Burcal C, Thomas AC, Hubbard T, Hj J, Ac T. Cortical Activity Relates to Injury Severity in Chronic Ankle Instability Patients. *J Athl Train.* 2017;52(6).
41. Baumeister J, Reinecke K, Schubert M, Weiß M. Altered electrocortical brain activity after ACL reconstruction during force control. *J Orthop Res.* 2011;29(9):1383-1389. doi:10.1002/jor.21380
42. Nashner L, Berthoz A. Visual contribution to rapid motor responses during postural control. *Brain Res.* 1978;150(2):403-407. doi:10.1016/0006-8993(78)90291-3
43. McKeon PO, Hertel J. Spatiotemporal postural control deficits are present in those with chronic ankle instability. *BMC Musculoskelet Disord.* 2008;9:76. doi:10.1186/1471-2474-9-76
44. Mckeon PO, Hertel J. Systematic Review of Postural Control and Lateral Ankle Instability, Part I: Can Deficits Be Detected With Instrumented Testing? *J Athl Train.* 2008;43(3):293-304.
<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2386423/pdf/attr-43-03->

293.pdf. Accessed April 9, 2018.

45. Medina McKeon JM, McKeon PO. Evaluation of Joint Position Recognition Measurement Variables Associated With Chronic Ankle Instability: A Meta-Analysis. *J Athl Train*. 2012;47(4):444-456. doi:10.4085/1062-6050-47.4.15
46. Mckeon PO, Ingersoll CD, Kerrigan DC, Saliba E, Bennett BC, Hertel J. Balance training improves function and postural control in those with chronic ankle instability. *Med Sci Sports Exerc*. 2008;40(10):1810-1819. doi:10.1249/MSS.0b013e31817e0f92
47. Wikstrom EA, Hubbard-Turner T, McKeon PO. Understanding and Treating Lateral Ankle Sprains and their Consequences: A Constraints-Based Approach. *Sport Med*. 2013;43(6):385-393. doi:10.1007/s40279-013-0043-z
48. Kim K-M, Best TM, Aiyer A. How Do Athletes with Chronic Ankle Instability Suffer from Impaired Balance? An Update on Neurophysiological Mechanisms. *Curr Sports Med Rep*. 2017;16(5):309-311. doi:10.1249/JSR.0000000000000407
49. Needle AR, Buz Swanik C, Schubert M, et al. Decoupling of laxity and cortical activation in functionally unstable ankles during joint loading. *Eur J Appl Physiol*. 2014;114:2129-2138. doi:10.1007/s00421-014-2929-3
50. Wolfe MW, Clinic L-G, Virginia S, Uhl TL, Mattacola CG. Management of Ankle Sprains. *JANUARY 1*. 2001;63(1). <http://www.aafp.org/afp/2001/0101/p93.pdf>. Accessed October 28, 2017.
51. Braun BL. Effects of ankle sprain in a general clinic population 6 to 18 months after medical evaluation. *Arch Fam Med*. 1999;8:143-148. doi:10.1001/archfami.8.2.143
52. Cooke MW, Lamb SE, Marsh J, Dale J, Cooke M. A survey of current consultant practice of treatment of severe ankle sprains in emergency departments in the United Kingdom. *Emerg Med J*. 2003;20:505-507. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1726246/pdf/v020p00505.pdf>. Accessed October 5, 2017.

53. Hutt K, Redding E. The Effect of an Eyes-closed Dance-specific Training Program on Dynamic Balance in Elite Pre-professional Ballet Dancers. *J Danc Med Sci*. 2014;18(1):3-11. doi:10.12678/1089-313X.18.1.3
54. Taube W, Gruber M, Beck S, Faist M, Gollhofer A, Schubert M. Cortical and spinal adaptations induced by balance training: Correlation between stance stability and corticospinal activation. *Acta Physiol*. 2007;189(4):347-358. doi:10.1111/j.1748-1716.2007.01665.x
55. EILS E, ROSENBAUM D. A multi-station proprioceptive exercise program in patients with ankle instability. *Med Sci Sport Exerc*. 2001;33(12):1991-1998. doi:10.1097/00005768-200112000-00003
56. Thompson C, Schabrun S, Romero R, Bialocerkowski A, van Dieen J, Marshall P. Factors Contributing to Chronic Ankle Instability: A Systematic Review and Meta-Analysis of Systematic Reviews. *Sport Med*. 2017;(September). doi:10.1007/s40279-017-0781-4
57. Patla AE. Understanding the roles of vision in the control of human locomotion. *Gait Posture*. 1997;5(1):54-69. doi:10.1016/S0966-6362(96)01109-5
58. Abernethy B. Enhancing sports performance through clinical and experimental optometry. *J Aust Optom Assoc*. 1986;69(5):189-196.
59. Committee on Vision National Research Council. *Emergent Techniques for Assessment of Visual Performance*.; 1985. doi:10.17226/916
60. Wade MG, Jones G. The role of vision and spatial orientation in the maintenance of posture .(Balance Special Series) The role of vision and spatial orientation in the maintenance of posture .(Balance Special Series). *Phys Ther*. 1997;619(June):1-10.
61. Freeman EE, Muñoz B, Turano KA, West SK. Measures of visual function and their association with driving modification in older adults. *Investig Ophthalmol Vis Sci*. 2006;47(2):514-520. doi:10.1167/iovs.05-0934
62. Lilly P. Nike's stroboscopic eyewear improves visual memory, hand-eye

coordination - ExtremeTech. <https://www.extremetech.com/extreme/133529-nikes-stroboscopic-eyewear-improves-visual-memory-hand-eye-coordination>. Published 2012. Accessed November 8, 2017.

63. Smith TQ, Mitroff SR. Stroboscopic Training Enhances Anticipatory Timing. *Int J Exerc Sci*. 2012;5(4):344-353. <http://www.ncbi.nlm.nih.gov/pubmed/27182391>. Accessed November 6, 2017.
64. Gregory Appelbaum L, Cain Julia E Schroeder MS, Darling EF, Mitroff SR. Stroboscopic visual training improves information encoding in short-term memory. 2012. <https://link-springer-com.libproxy.lib.unc.edu/content/pdf/10.3758%2Fs13414-012-0344-6.pdf>. Accessed September 23, 2017.
65. Gregory Appelbaum L, Schroeder JE, Cain MS, Mitroff SR, Wallis TSA, Lu Z-L. Improved visual cognition through stroboscopic training. 2011. doi:10.3389/fpsyg.2011.00276
66. Silva P, Lott R, Wickrama K a S, Mota J, Welk G. Stroboscopic vision to induce sensory reweighting during postural control. *Int J Sport Nutr Exerc Metab*. 2011;32:1-44. doi:10.1123/ijsspp.2015-0012
67. Erickson GB, Citek K, Cove M, et al. Reliability of a computer-based system for measuring visual performance skills. *Optometry*. 2011;82:528-542. doi:10.1016/j.optm.2011.01.012
68. Guskiewicz KM, Ross SE, Marshall SW. *Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes*. Vol 36. Association, Inc; 2001. www.journalofathletictraining.org. Accessed February 23, 2019.
69. Hertel J, Olmsted-Kramer LC. Deficits in time-to-boundary measures of postural control with chronic ankle instability. doi:10.1016/j.gaitpost.2005.12.009
70. Hertel J, Olmsted-Kramer LC, Challis JH. *Time-to-Boundary Measures of Postural Control During Single Leg Quiet Standing*. Vol 22.; 2006. <https://pdfs.semanticscholar.org/f7e8/2c0fff80db3e1bc31b7aeea7dacbc2c99ff4.pdf>. Accessed February 23, 2019.

71. Van Emmerik REA, Van Wegen EEH. On the functional aspects of variability in postural control. *Exerc Sport Sci Rev.* 2002;30(4):177-183. doi:10.1097/00003677-200210000-00007
72. Wikstrom EA, Fournier KA, Mckeen PO. Postural control differs between those with and without chronic ankle instability. *Gait Posture.* 32:82-86. doi:10.1016/j.gaitpost.2010.03.015
73. Kim K-M, Kim J-S, Kim K-M, Kim J-S, Grooms DR. Stroboscopic Vision to Induce Sensory Reweighting During Postural Control. *J Sport Rehabil.* 2017. doi:10.1123/jsr.2017-0035
74. Hazime FA, Allard P, Ide MR, Siqueira CM, Amorim CF, Tanaka C. Postural control under visual and proprioceptive perturbations during double and single limb stances: Insights for balance training. *J Bodyw Mov Ther.* 2012;16(2):224-229. doi:10.1016/j.jbmt.2011.02.003
75. Tarantola J, Nardone A, Tacchini E, Schieppati M. Human stance stability improves with the repetition of the task: Effect of foot position and visual condition. *Neurosci Lett.* 1997;228(2):75-78. doi:10.1016/S0304-3940(97)00370-4
76. Hertel J. Sensorimotor Deficits with Ankle Sprains and Chronic Ankle Instability. doi:10.1016/j.csm.2008.03.006
77. Knill DC, Pouget A. The Bayesian brain: the role of uncertainty in neural coding and computation. *Opin TRENDS Neurosci.* 2004;27(12). doi:10.1016/j.tins.2004.10.007
78. Kabbaligere R, Lee B-C, Layne CS. Balancing sensory inputs: Sensory reweighting of ankle proprioception and vision during a bipedal posture task. 2017. doi:10.1016/j.gaitpost.2016.12.009
79. Guskiewicz KM, Ross SE, Marshall SW. *Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes.* Vol 36. Association, Inc; 2001. www.journalofathletictraining.org. Accessed March 27, 2019.

80. Erickson G. Visual Performance on the Nike Sensory Station Compared to the Senaptec Sensory Station. <https://www.aaopt.org/detail/knowledge-base-article/visual-performance-nike-sensory-station-compared-senaptec-sensory-station>. Accessed January 26, 2019.
81. Horiuchi K, Ishihara M, Imanaka K. The essential role of optical flow in the peripheral visual field for stable quiet standing: Evidence from the use of a head-mounted display. 2017. doi:10.1371/journal.pone.0184552
82. Shamir RR, Friedman Y, Joskowicz L, Mimouni M, Blumenthal EZ. Comparison of Snellen and Early Treatment Diabetic Retinopathy Study charts using a computer simulation. *Int J Ophthalmology*. 2016;9(1):119-123. doi:10.18240/ijo.2016.01.20
83. Thakur S, Ichhpujani P, Suresh Kumar •, Kaur R, Sood S. Assessment of contrast sensitivity by Spaeth Richman Contrast Sensitivity Test and Pelli Robson Chart Test in patients with varying severity of glaucoma. *Eye*. 2018;32:1392-1400. doi:10.1038/s41433-018-0099-y
84. Chetana N, Jayesh R. Subjective Visual Vertical in Various Vestibular Disorders by Using a Simple Bucket Test. *Indian J Otolaryngol Head Neck Surg*. 2015;67(2):180-184. doi:10.1007/s12070-014-0760-0
85. Erickson GB, Citek K, Cove M, et al. Reliability of a computer-based system for measuring visual performance skills. 2011. doi:10.1016/j.optm.2011.01.012